

# **Acoustic Monitoring of Flow Through the Strait of Gibraltar: Data Analysis and Interpretation**

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## **LONG-TERM GOALS**

Existing techniques do not begin to exploit the full potential of acoustic remote sensing methods to study ocean thermal structure and circulation. This research is intended to improve our understanding of acoustic propagation in shallow-to-intermediate depth environments and to extend tomographic techniques to ocean regimes in which acoustic propagation is more complex than the largely deep-water cases studied to date.

## **OBJECTIVES**

The Strait of Gibraltar is a challenging environment in which to work. Internal undular bores of 100 m amplitude propagate along the interface between an upper layer of Atlantic water and a lower layer of Mediterranean water, eventually evolving into a packet of internal solitary waves. The interface is also strongly modulated by internal tides of comparable amplitude. High-frequency, broadband, underwater acoustic transmissions across the Strait are used to examine acoustic scattering caused by this unique internal wave field and the feasibility of acoustically remote sensing physical processes in the Strait. The specific issues addressed in this project are: (i) to determine whether one or more acoustic ray paths exist (at 2 kHz) that are resolvable, identifiable, stable, and that provide useful integral measures of the flow; (ii) to measure acoustic scattering due to the internal wave bores in the Strait; and (iii) to study normal mode propagation (at 250 Hz), including the feasibility of using modal analyses, matched field tomography, and full-field inversion techniques to obtain information on the temperature and current fields. Our goal is to obtain a much better understanding of acoustic propagation in the complex oceanographic environment present in the Strait of Gibraltar and, by extension, in other straits that are two-layer systems. We also wish to determine which of the various possible acoustic methods for monitoring the transport in the Strait works best, and just how well the various methods tried do work.

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## APPROACH

A short-term feasibility test was conducted during April-May 1996, during which differential travel times (at 2 kHz), horizontal ray arrival angles (at 2 kHz), and normal mode group delays and amplitudes (at 250 Hz) were measured as potential observables for use in the inverse problem for ocean sound speed and current. Extensive independent measurements of the temperature, salinity, and velocity fields in the Strait were made. Satellite synthetic aperture radar (SAR) images of the Strait were acquired to provide information on the evolution of the internal wave bores. Three current meter moorings provided data spanning the Strait near its eastern end. Extensive forward modeling of the acoustic propagation in the Strait, using a variety of propagation codes, a synthesis of the sound speed and current meter data, and models for the internal wave bore structure as a function of space and time have been done. Good matches both help to explain the acoustic observations and allow us to extract more information from inverse methods.

## WORK COMPLETED

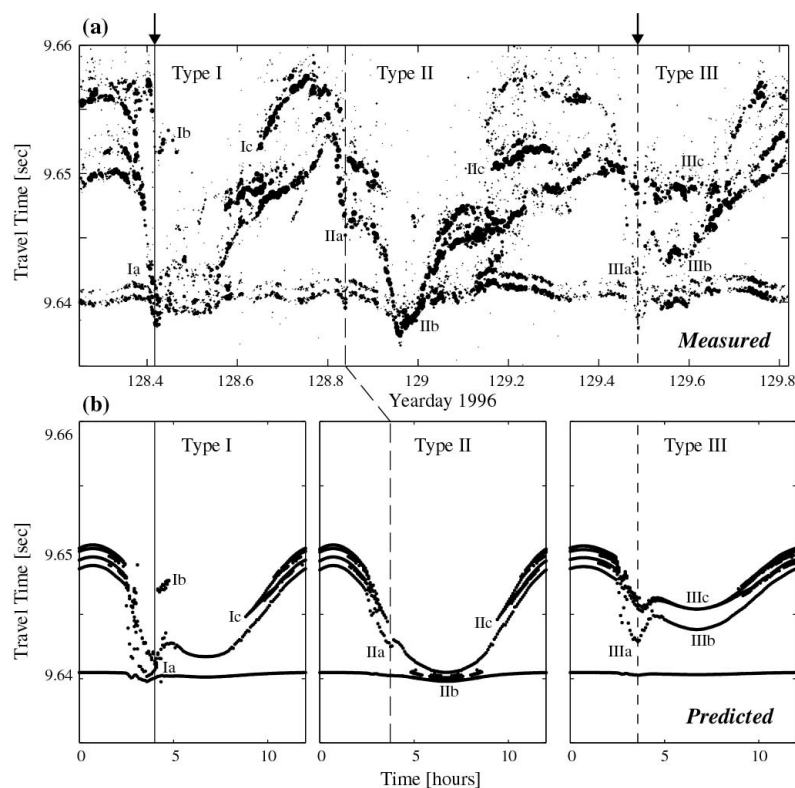
Observations of acoustic scattering due to internal solitary waves in the Strait have been found to compare favorably with predicted ray arrival patterns for propagation through a model of the internal wave bore with suitably chosen parameters (Tiemann *et al.*, 2000a). The feasibility of using acoustic remote sensing methods to routinely measure the properties of the internal solitary waves and internal tides in the Strait was subsequently explored. A number of useful acoustic observables were identified (Tiemann *et al.*, 2000b). Manuscripts on these efforts have been submitted, of which one is in press. C. Tiemann has completed his doctoral dissertation on this work and successfully defended it (Tiemann, 2000).

Integral measurements of mass transport and heat content in the Strait from acoustic transmissions have been found to compare favorably with moored current meter and temperature measurements (Send *et al.*, 2000). Of various potential acoustic approaches to measuring currents, including horizontal arrival angle measurements, scintillation techniques, and reciprocal transmissions, differential travel times from reciprocal transmissions were found to provide the most robust integral data. A manuscript on this research has been submitted and accepted.

## RESULTS

*Acoustic Scattering.* Although the observed acoustic scattering is quite complicated, it is surprisingly robust from one tidal cycle to the next, making it a good candidate for modeling. A model of the complex hydraulics in the Strait, when used in the acoustic forward problem, successfully reproduces many key features of the observed acoustic arrival pattern. Work with the model has shown that both internal solitary wave and internal tide effects must be combined to reproduce the observed acoustic channel impulse response; either one individually cannot explain all the travel time variability. Comparison between the spring and neap tide cases emphasizes the significant acoustic scattering caused by large-amplitude internal solitary wave packets. As internal solitary waves cross the acoustic path, they cause sharp sound-speed gradients that intermittently refract acoustic rays away from and into small-vertical-scale sound-speed channels present in the upper layer of the Strait. The results suggest that it might be feasible to use acoustic methods for remote sensing of internal solitary wave parameters.

*Acoustic Remote Sensing.* Internal bores crossing the acoustic path can be recognized by their scattering effects in the acoustic record. The time between internal bore crossings is influenced more by the tidal phase of the bore release at the Camarinal Sill than by variability in the bore's propagation time down the Strait, which was found here to average 5.4 hours for a mode 1 bore, in agreement with earlier work. When internal bores were present, the acoustic arrival patterns could be classified as one of three types with different internal bore and internal tide amplitudes (Figure 1). The arrival types alternate during spring to neap tide transitions, suggesting that internal bore amplitude is not linearly related to tidal height as has often been assumed previously. The sensitivities of acoustic observables to a number of physical parameters were investigated using the forward model, and linear inverse techniques provided estimates of physical parameters from spring tidal cycles. The time series was too short to provide useful oceanographic information, however.



**Figure 1. Measured and predicted ray travel times over three tidal cycles. The labels ('Ia' through 'IIIc') identify key features of the measured data matched by the model output. Vertical lines indicate times of internal bore crossings and arrival structure type (Type I solid, Type II long dash, Type III short dash). Arrows indicate times when the passage of the bore caused a large tilt of the southern acoustic transceiver.**

*Integral measurements of mass transport.* Reciprocal acoustic transmissions provide the most promising approach to measuring current in the lower layer (Mediterranean outflow) of the various possible methods that were tested. The fractional uncertainty in the lower layer tidal transport from a single tomographic path was estimated to be only 0.13 rms, which means that 98% of the *a priori* tidal transport variance was resolved. The spatial scales of the sub-tidal flow are thought to be significantly shorter than those of the tidal flow, however, which means that a more elaborate monitoring network is

required to achieve the same performance for sub-tidal variability. Finally, sum travel times from the reciprocal transmissions were found to provide good measurements of the temperature and heat content in the lower layer.

## **IMPACT/APPLICATIONS**

This research has the potential to affect the design of acoustic systems that must function in complex two-layer environments such as the Strait of Gibraltar, whether for acoustic remote sensing of the ocean interior or for other applications. Internal wave bores, in particular, appear to be more ubiquitous in shallow water than previously realized, making a full understanding of their impact on acoustic propagation crucial to predict the performance of acoustic systems.

Monitoring the variability of the transport through the Strait of Gibraltar is important for a wide range of oceanographic problems. Acoustic methods have the potential to directly provide spatially-averaged measures of the flow, and are therefore strong candidates for providing routine, rapidly repeated, transport measurements. This research could lead to the application of acoustic methods for long-term monitoring of transport in the Strait of Gibraltar and, by extension, in other similar straits.

## **TRANSITIONS**

None.

## **RELATED PROJECTS**

A preliminary equipment test in Knight Inlet was part of a much larger Knight Inlet Experiment led by D. Farmer (IOS, Canada). The Strait of Gibraltar experiment is a joint effort with U. Send (University of Kiel, Germany). In addition, we are collaborating with J. Apel (Global Ocean Associates), who is analyzing the SAR images.

## **PUBLICATIONS**

Send, U., P. F. Worcester, and B. D. Cornuelle, "An acoustic observing system for the Strait of Gibraltar," Proc. International Conference on the Ocean Observing System for Climate, St. Raphael, France, 18–22 October 1999 (in press, 2000).

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